Sunflower Response to Tillage and Nitrogen Fertilization under Intensive Cropping in a Wheat Rotation

Ardell D. Halvorson,* Alfred L. Black, Joseph M. Krupinsky, Stephen D. Merrill, and Donald L. Tanaka

ABSTRACT

Sunflower (*Helianthus annuus* L.) is a warm-season, intermediate water-use crop that can add diversity to dryland crop rotations. Reduced tillage systems may enhance sunflower yield in intensive cropping systems. A 12-year study was conducted to determine how sunflower cultivars of early and medium maturity respond to tillage system (conventional-till, CT; minimum-till, MT; no-till, NT) and N fertilization (34, 67, and 101 kg N ha^{-1}) within a dryland spring wheat (*Triticum aestivum* L.)–winter wheat–sunflower rotation. Averaged across N rates, cultivars, and years, sunflower seed yields were greater with MT (1550 kg ha^{-1}) than with NT (1460 kg ha^{-1}) and CT (1450 kg ha^{-1}). Increasing N rate above 34 kg N ha^{-1} generally increased grain yield, but varied from year to year. The tillage $\times$ N interaction showed that the highest seed yields were obtained with NT (1638 kg ha^{-1}) and MT (1614 kg ha^{-1}) at 101 kg N ha^{-1}. Total plant-available water (TPAW) of $<$350 mm greatly reduced sunflower yield potential, due to water stress, compared with yields for 350 to 500 mm of TPAW. TPAW $>$ 500 mm did not result in increased sunflower yields over those with 350 to 500 mm TPAW. Yield differences between cultivar maturity classes varied from year to year and with tillage and N level. At the lowest N rate, weeds were more problematic in NT than in CT and MT plots. More N fertilizer may be needed with NT to optimize sunflower yields than with CT and MT, because of less residual soil NO_3–N with NT. Results indicate that producers in the northern Great Plains can use sunflower successfully in annual cropping systems, particularly if MT and NT are used with adequate N fertilization.

WATER is a major factor limiting crop production in the northern Great Plains. Farmers and ranchers need to manage crop rotations, crop residues, and tillage system to effectively store and use the limited precipitation received. No-till (NT) and minimum-till (MT) systems are more efficient than conventional-till (CT) systems in conserving precipitation for crop production (Aase and Schaefer, 1996; Halvorson, 1990a; McGee et al., 1997; Peterson et al., 1996; Tanaka and Anderson, 1997). The traditional crop–fallow system of dryland farming utilizes water (precipitation) inefficiently and results in the development of saline seeps in the Great Plains (Halvorson and Black, 1974; Halvorson, 1990b). Because NT and MT systems are more efficient than CT systems in conserving precipitation, use of NT or MT systems would accentuate the saline-seep problem without accruing the benefit of more efficient use of stored soil water from more intensive cropping systems than crop–fallow (Halvorson, 1984; Halvorson, 1990b).

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Black et al. (1981) reported more efficient water use with more intensive cropping systems. When precipitation storage efficiency improves, as is possible with MT and NT, producers can increase their success of cropping more intensively than with crop–fallow (Halvorson and Reule, 1994a, 1994b; McGee et al., 1997; Peterson et al., 1996). Aase and Schaefer (1996) reported that NT annual-cropped spring wheat was more profitable and productive than spring wheat–fallow in a 356 mm precipitation zone in northeast Montana.

Sunflower is a deep-rooted crop, intermediate in water use, that can extract soil water from below root zones of normal small grain crops (Alessi et al., 1977; Berglund, 1994; Lindstrom et al., 1982; Merrill et al., 1994; Unger, 1984). Sunflower therefore has the potential to improve water-use efficiency in rotation with small-grain crops. Sunflower is also a desirable warm-season crop for including in more intensive dryland crop rotations because it provides diversity to the rotations (spreading out workload, breaking weed and disease cycles, and spreading out risk) and is thought to be drought tolerant (Lamond et al., 1985; Lindstrom et al., 1982; Unger, 1984; Vijayalakshmi et al., 1975).

Use of MT and NT systems may provide sufficient soil water storage to produce economical yields of sunflower in intensive cropping systems in the northern Great Plains. Shorter-season or early-maturity sunflowers may have a yield advantage over longer-season cultivars in dryland rotations if crop water supplies become limiting or if the growing season is cut short by early fall frost. Our objective was to determine how sunflower cultivars respond to tillage and N fertilization within a dryland spring wheat–winter wheat–sunflower rotation (annual cropping system) in the northern Great Plains.

MATERIALS AND METHODS

The study was initiated in 1984 on a Temvik–Wilton silt loam soil (fine-silty, mixed, superactive, frigid Typic Haplustolls–Pachic Haplustolls) near Mandan, ND. Surface soil pH was 6.4, soil organic C was 21.4 g kg^{-1}, and soil test P was 20 to 26 mg kg^{-1} in the spring of 1984 (Black and Tanaka, 1997). Data collection was from 1985 through 1996. An annual cropping rotation consisting of spring wheat–winter wheat–sunflower (SW–WW–SF) was managed under three tillage systems: CT, MT, and NT (Halvorson et al., 1999). Nitrogen fertilizer was applied in early spring each year as a broadcast application of NH_4NO_3 at rates of 34, 67, and 101 kg N ha^{-1}, except for 1991 and 1992, when no N was applied because of a build-up of residual soil NO_3–N due to drought conditions and low yields in 1989 and 1990. Two sunflower cultivars were grown each year, with early and medium relative maturity

Abbreviations: CT, conventional-till; MT, minimum-till; NT, no-till; PAW, plant-available water; SF, sunflower; SW, spring wheat; TPAW, total plant-available water; WW, winter wheat.

Table 1. Sunflower cultivars grown and residual herbicides applied each year under conventional-till (CT), minimum-till (MT), and no-till (NT) management near Mandan, ND.

Year	Early-maturity cultivar	Time to maturity	Medium-maturity cultivar	Time to maturity	Residual herbicide applied† CT	MT	NT
		d		d			
1985	Sokota 2057	92	USDA 894	96	trifluralin	trifluralin	oryzalin
1986	Sokota 2057	92	Sokota 4000	98	trifluralin	trifluralin	oryzalin
1987	Sokota 2057	92	Sokota 4000	98	trifluralin	trifluralin	oryzalin
1988	Sokota 2057	92	AgroPro 3900	94	trifluralin	trifluralin	oryzalin
1989	Sokota 2057	92	AgroPro 2036	95	trifluralin	trifluralin	oryzalin
1990	Sokota 2057	92	AgroPro 4040	94	trifluralin	trifluralin	oryzalin
1991	Sigco 452	94	Sigco 458	95	ethalfluralin	ethalfluralin	oryzalin
1992	Sigco 458	95	Sigco 658	97	ethalfluralin	ethalfluralin	oryzalin
1993	Sigco 651	89	Sigco 658	97	ethalfluralin	ethalfluralin	oryzalin
1994	Sigco 651	89	Sigco 658	97	ethalfluralin	ethalfluralin	ethalfluralin
1995	Sigco 651	89	Sigco 658	97	ethalfluralin	ethalfluralin	ethalfluralin
1996	Sigco 651	89	Sigco 658	97	ethalfluralin	ethalfluralin	ethalfluralin

† Trifluralin, 2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)benzenamine; ethalfluralin, *N*-ethyl-*N*-(2-methyl-2-propenyl)-2,6-dinitro-4-(trifluoromethyl)benzenamine; oryzalin, 4-(dipropylamino)-3,5-dinitrobenzenesulfonamide).

dates (Table 1).[1] Cultivars were changed during the study period as improved cultivars became available or seed became unavailable. Each main block of the study was 137.2 by 73.1 m, with tillage plots being 45.7 by 73.1 m, N plots 45.7 by 24.4 m, and cultivar plots 22.8 by 24.4 m. Tillage plots were oriented in a north–south direction, N plots in an east–west direction across tillage plots, and cultivars in a north–south direction within tillage plots and across N plots. Triplicate sets of plots were established to allow all phases of the rotation to be present each year. Experimental design was a strip-strip-split-plot design, with tillage and N treatments stripped and cultivar as subplots with three replications.

All tillage treatments were sprayed with glyphosate [*N*-(phosphonomethyl)glycine] and 2,4-D [(2,4-dichlorophenoxy) acetic acid] herbicides following WW harvest from 1985 through 1994. In 1995 and 1996, the CT and MT plots were undercut with a sweep plow (81 cm blades on 66-cm spacings) at a 5- to 8-cm depth following WW harvest. The CT plots were undercut at a shallow depth (5–8 cm) with a sweep plow in early spring at time of granular herbicide application (Table 1), then disked at a depth of 8 to 12 cm for a second herbicide incorporation about 10 d later, resulting in surface residue cover generally <30% at planting. The MT plots were undercut at a shallow depth (5–8 cm) with a sweep plow in early spring at time of granular herbicide application (Table 1), followed by a second undercut operation with the sweep plow about 10 d later for a second herbicide incorporation, resulting in 30 to 60% residue cover at planting. A late fall (late October or early November) application of granular herbicide with no incorporation was made on NT plots. Glyphosate was applied to NT plots in the spring prior to planting, resulting in surface residue cover generally >60% at planting. Tillages and herbicides applied to the previous WW crop are described by Halvorson et al. (1999). Residue cover estimates were visual observations based on experience with photographic measurements made of residue cover in adjacent SW–fallow plots (Merrill et al., 1995).

Sunflower was generally planted in late May at a rate of about 54 thousand seeds ha^{-1} with a NT row crop planter at a 91-cm row spacing, except for 1996, when a 76-cm row spacing was used. Plots were generally aerial-sprayed once during the growing season with an insecticide, to reduce insect damage. Sunflower seed yield was determined generally in early October each year by hand-cutting head samples from two 5-m^2 areas within each plot. Seed yields were expressed on a 100 g kg^{-1} moisture content basis.

Soil samples, one 3-cm-diameter core per plot, were collected from one cultivar plot for each tillage and N fertilizer treatment each spring (April) before N fertilization for gravimetric soil water and NO_3–N analyses. Samples were collected in 30-cm increments to a depth of 150 cm. Soil NO_3–N was determined by autoanalyzer (Lachat Instruments, 1989; Technicon Industrial Systems, 1973) on a 5:1 extract to soil ratio using 2 *M* KCL extracting solution from 1985 to 1993 and a 0.01 *M* $CaSO_4$ extracting solution from 1993 through 1996. A factor of four was used to convert soil NO_3–N extract values to kg ha^{-1} for each 30-cm depth increment. Volumetric soil water content was estimated from gravimetric soil water measurements using a soil bulk density of 1.42 g cm^{-3} for the profile. Total plant-available water (TPAW) was estimated as the sum of spring soil plant-available water (PAW) in the 0- to 150-cm profile plus growing season precipitation (May–September). Spring soil PAW was estimated by subtracting the lowest measured soil water content (152 mm) in the 0- to 150-cm profile following SF harvest during the 12-year study from soil water contents in the 0- to 150-cm soil profile each spring. Precipitation was measured with a recording rain gauge at the site from April through October each year. November through March precipitation was estimated from U.S. Weather Service measurements made at the Northern Great Plains Research Laboratory at Mandan, approximately 5 km northeast of the site.

Analysis of variance procedures were conducted using SAS statistical procedures (SAS Inst., 1991), with years treated as a fixed effect. All differences discussed are significant at the $P = 0.05$ probability level unless otherwise stated. An LSD was calculated only when the analysis of variance *F*-test was significant at the $P = 0.05$ probability level.

RESULTS AND DISCUSSION

Precipitation

Annual precipitation (Fig. 1) varied considerably over the 12-year period from 1985 through 1996. Growing season (May–September) precipitation also varied from year to year, with similar trends to that of annual precipitation. Growing season precipitation was lowest (146 mm) in 1988 and highest (574 mm) in 1993. Three consecutive drought years (1988–1990) provided an opportunity to evaluate the effects of water stress on sunflower

[1] Trade names and company names are included for the benefit of the reader and do not imply any endorsement or preferential treatment of the product by the USDA-ARS.

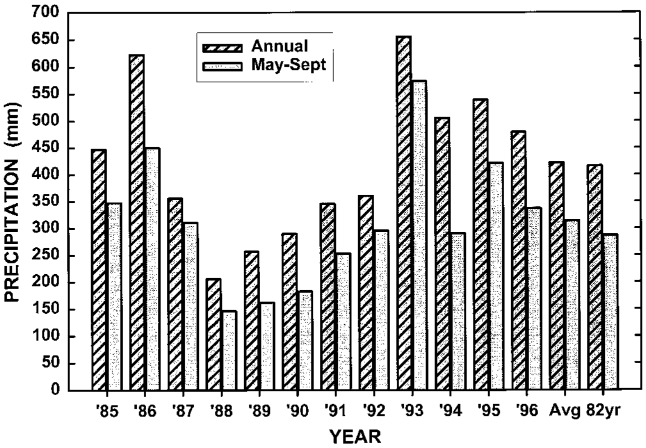

Fig. 1. Annual and growing season (May–September) precipitation at the study site, along with the 82-year average precipitation at the nearby Northern Great Plains Research Laboratory, Mandan, ND.

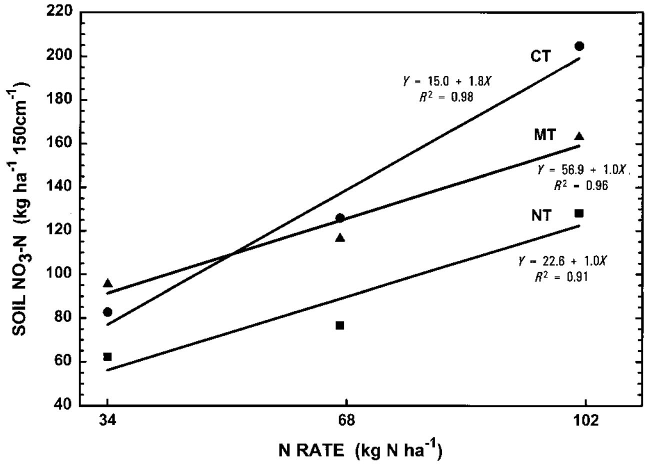

Fig. 3. Spring soil NO_3–N in the 0- to 150-cm soil profile as a function N fertilizer rate for each tillage treatment, averaged across 12 years. Tillage × N Rate interaction LSD (0.05) = 24 kg N ha^{-1}.

production in this annual cropping system. Total plant-available water (TPAW) was <300 mm in these 3 years (Fig. 2), resulting in severe plant water stress, reduced growth, and reduced seed yield potential. Annual and growing season precipitation in 1986, 1993, and 1995 were above average (Fig. 1). Total plant-available water was considered above average for the experiment in 1986, 1993, 1994, and 1996 (Fig. 2). Averaged across years, TPAW was greater ($P = 0.009$) with NT (456 mm) than with MT (441 mm) or CT (433 mm). However, the tillage × year interaction ($P = 0.05$) showed that the effects of tillage on TPAW varied with year (Fig. 2). In 1986 and 1993, there was more TPAW with NT than with MT or CT. In 1992 and 1996, TPAW was greater with NT than CT. Differences in TPAW among tillage treatments were not significant for the other years, based on the interaction LSD presented in Fig. 2. The level of TPAW was significantly different ($P = 0.0001$) among years, except for 1988 and 1989, which were not different.

Soil NO_3–N

Averaged across years and N rates, spring soil NO_3–N levels in the 0- to 150-cm depth were lower in NT (89 kg N ha^{-1}) than in CT (138 kg N ha^{-1}) or MT (125 kg N ha^{-1}). This probably reflects the effects of tillage in increasing the amount of N mineralized in the CT and MT plots. Wienhold and Halvorson (1998) showed that NT had a higher level of total N in the surface 15 cm of soil than did the MT and CT treatments after 10 crop years. The tillage × N interaction ($P = 0.04$) is shown in Fig. 3. Averaged across years, spring soil NO_3–N in the 0- to 150-cm profile increased as the N fertilization rate increased with all tillage systems. At the 34 kg N ha^{-1} rate, soil N was lower with NT than with MT. At the 67 kg N ha^{-1} rate, spring soil N was lower with NT than MT or CT. At the 101 kg N ha^{-1} rate, spring soil N levels were CT > MT > NT. Spring soil NO_3–N levels in the 0- to 150-cm profile increased substantially in 1990 following the low wheat yields in 1988 and 1989, due to drought, as shown in Fig. 4 by the N × year interaction ($P = 0.0001$).

Seed Yield

Sunflower seed yield responses were attributable to tillage system ($P = 0.03$), N fertilization ($P = 0.0001$), and year ($P = 0.0001$), but not to cultivar maturity class

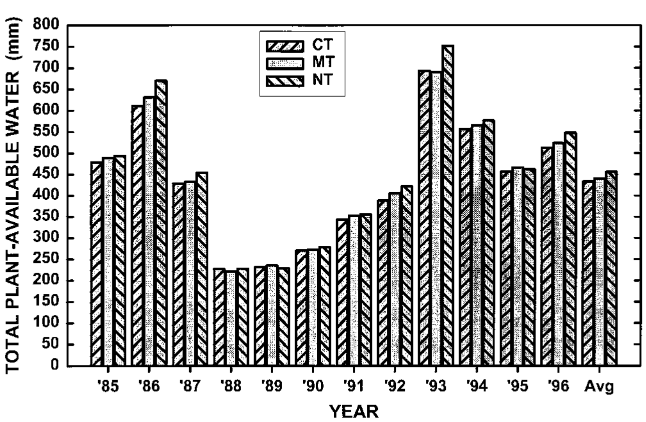

Fig. 2. Growing season total plant-available water (TPAW) as a function of year and tillage treatment. Tillage × Year interaction LSD (0.05) = 33 mm.

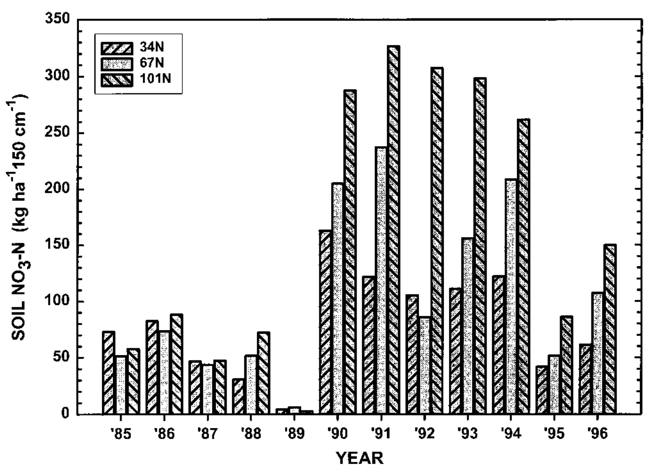

Fig. 4. Spring soil NO_3–N in the 0- to 150-cm soil profile as a function of years for three N fertilizer rates. LSD (0.05) = 55 kg ha^{-1}.

(P = 0.28). Also, the tillage × N (P = 0.01), tillage × year (P = 0.0001), N × year (P = 0.0001), and tillage × N × cultivar × year (P = 0.03) interactions were significant and will be discussed individually. Year data were arbitrarily grouped by level of TPAW (<350 mm, 350–500 mm, and >500 mm), to show the relationship of TPAW on sunflower seed yields.

Averaged across years, N rate, and cultivars, MT (1550 kg ha^{-1}) resulted in greater yield than NT (1460 kg ha^{-1}) and CT (1450 kg ha^{-1}). Averaged across tillage, cultivars, and years, sunflower seed yields increased ($LSD_{0.05}$ = 26 kg ha^{-1}) with increasing N rate; 1390, 1490, and 1590 kg ha^{-1} for the 34, 67, and 101 kg N ha^{-1} treatments, respectively. Averaged across years, tillages, and N rates, seed yields were similar (1500 and 1470 kg ha^{-1}) for the early- and medium-maturity cultivars, respectively.

The tillage × N rate × cultivar × year interaction is shown in Table 2. Although TPAW was low in 1988 (Fig. 2), sunflower in 1988 responded to N fertilization and had greater seed yields than in 1989, 1990, and 1991 (Table 2). Apparently, sufficient soil water was used from below the wheat root zone to result in a reasonable sunflower yield in 1988. The 1988 sunflower yields contrast with the very low (<250 kg ha^{-1}) spring wheat and winter wheat grain yields in 1988 (Halvorson et al., 1999). The 1989 sunflower yields (2nd year of drought) decreased with increasing N rate for the CT and MT treatments and were greater than the 1990 sunflower yields. The 1990 sunflower yields (3rd year of drought) were the lowest obtained during the study and were greater with NT than with CT or MT. The low 1990 yield reflects the fact that little water recharge of the deeper soil profile had occurred, even though 1990 precipitation (Fig. 1) was greater than in 1988. The 1990 sunflower crop followed the 1987 sunflower crop, which dried the deeper soil profile with little soil water recharge in 1988 following spring wheat or in 1989 following winter wheat. Thus, the importance of soil water recharge at deeper depths for sunflower production is indicated. Sunflower not only roots deeper than does spring wheat or winter wheat, it tends to remove more water from a given soil volume than spring wheat or winter wheat. Thus, it takes more water to recharge the soil profile following sunflower than following spring wheat or winter wheat. In the <350 mm TPAW group

Table 2. Sunflower seed yields near Mandan, ND, as a function of N fertilization rate, tillage, cultivar maturity class, and year, grouped by level of total plant-available water (TPAW). Significant N rate × tillage × cultivar × year interaction.†

	Seed yield								
	34 kg N ha^{-1}			67 kg N ha^{-1}			101 kg N ha^{-1}		
Year	CT‡	MT	NT	CT	MT	NT	CT	MT	NT
	kg ha^{-1}								
	Early maturity (TPAW < 350 mm)								
1988	791	915	882	940	1054	1006	935	1167	1173
1989	442	875	737	406	946	669	238	502	839
1990	153	34	468	163	43	659	61	64	505
1991	185	469	512	313	762	279	430	419	536
	Early maturity (TPAW 350–500 mm)								
1985	2060	2343	2123	2222	2527	2289	2330	2537	2474
1987	1975	2149	1951	2201	2222	2388	2260	2240	2360
1992	2126	1998	1589	2081	1886	1420	2009	2161	2279
1995	1775	2004	952	2001	1865	1261	2036	2174	1791
	Early maturity (TPAW > 500 mm)								
1986	1915	1870	1658	2059	2267	1927	2329	2349	2375
1993	1668	1694	1770	1633	1897	1906	1497	1761	1776
1994	2037	2031	2143	1801	1858	1909	2008	2032	1913
1996	1557	1488	1232	1674	1868	1851	1804	2118	2160
	Medium maturity (TPAW < 350 mm)								
1988	761	827	730	900	1006	924	1051	1108	1010
1989	366	697	811	464	832	783	340	480	809
1990	266	15	444	181	12	543	12	19	692
1991	246	535	685	198	369	573	203	669	619
	Medium maturity (TPAW 350–500 mm)								
1985	2313	2252	2500	2502	2516	2493	2673	2523	2829
1987	1906	1724	1888	1808	2403	1783	1977	2199	2064
1992	2109	2072	1297	2238	1983	1418	2335	2239	1851
1995	1713	1814	735	1782	1979	1143	2042	2218	1641
	Medium maturity (TPAW > 500 mm)								
1986	1976	2203	1649	2338	2362	2032	2544	2525	2351
1993	1667	1718	1161	1716	1613	1665	1509	1740	1702
1994	1716	1729	1801	1729	1870	1824	1795	1898	1813
1996	1565	1725	1619	1612	1745	1496	1621	1594	1754

† N rate × tillage × cultivar × year interaction LSD (0.05) = 267 kg ha^{-1}.
‡ CT, conventional tillage; MT, minimum tillage; NT, no-till.

(Table 2), cultivar maturity classes responded similarly to the drought stress.

In the 350- to 500-mm TPAW group (Table 2), sunflower response to N was greatest with NT, which could be expected, given the lower level of spring soil N (Fig. 3). Cultivar maturity class effects on yields were variable from year to year. For example, the medium-maturity cultivar tended to yield better than the early cultivar in 1985, but the reverse appeared to be true in 1987. Changes in cultivars from year to year (Table 1) probably contributed to variation in response to cultivar class, which may have been partly responsible for the four-way interaction. Except for 1985, yields with NT tended to be greater with early than with medium-maturity cultivars.

In the >500 mm TPAW group (Table 2), sunflower yields tended to be similar to those of the 350- to 500-mm TPAW group. Except for 1986, response to N fertilization was minimal above 34 kg N ha^{-1}, probably due to the build-up of residual soil N (Fig. 4) with higher N rates following the drought years of 1988 to 1990. In 1996, the early-maturing cultivar responded to N rates above 34 kg N ha^{-1}, but the medium-maturing cultivar did not. The early-maturing cultivar tended to yield better than the medium-maturing cultivar in 1993, 1994, and 1996. This response was probably due to the cool, wet years, in which the reduced growing season heat units tended to favor shorter-season cultivars. At the highest rate of N fertilization, NT sunflower yields were greater than those of CT in 1993 and 1996 for the early-maturity cultivar.

The tillage × N rate interaction on sunflower seed yield is shown in Fig. 5. Averaged across 12 years, NT and MT with 101 kg N ha^{-1} resulted in the highest sunflower seed yields. At the 34 kg N ha^{-1} rate, yields with NT were reduced relative to those under MT and CT, probably because of the lower level of residual soil NO_3–N with NT (Fig. 3). At the 67 kg N ha^{-1} rate, MT resulted in the greatest yield, with yields being similar between NT and CT. Sunflower yield responses to increasing N rate were greatest with NT. This was reasonable, in that spring soil NO_3–N levels were lower with NT than with CT or MT (Fig. 3). These data indicate that a higher level of N fertilization may be needed to optimize seed yields with NT than with MT and CT, due to the lower level of spring soil NO_3–N with NT.

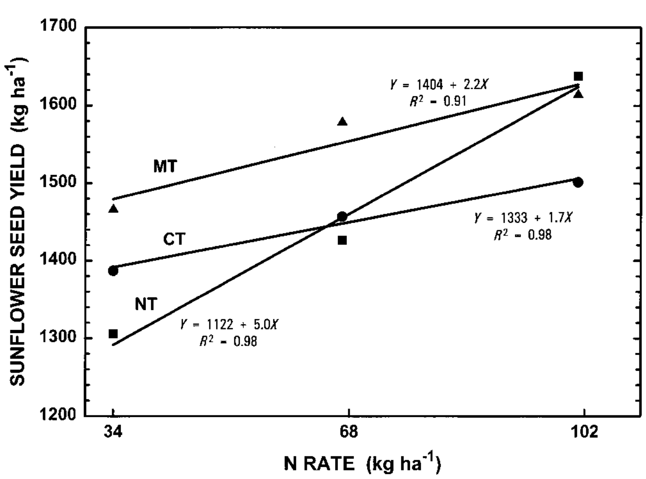

Fig. 5. Average 12-year sunflower seed yield as a function of N fertilizer rate for three tillage treatments. Tillage × N Rate interaction LSD (0.05) = 84 kg ha^{-1}.

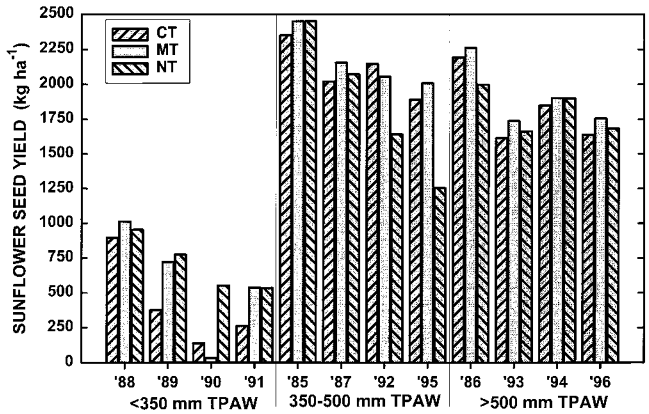

Fig. 6. Sunflower seed yield as a function of year for three tillage treatments grouped by level of total plant-available water (TPAW). Tillage × Year interaction LSD (0.05) = 254 kg ha^{-1}.

The interaction of tillage × year on sunflower seed yield is shown in Fig. 6. Sunflower yields, except for 1990, were generally greater for MT and NT than for CT in the <350 mm TPAW group, demonstrating the benefits of MT and NT systems in efficiently utilizing water. In the 350- to 500-mm TPAW group, MT generally resulted in the highest yield level. Yields with NT were lower than those with CT and MT in 1986, 1992 and 1995, basically because yields with NT were less than those with CT and MT at the 34 and 67 kg N ha^{-1} rates (Table 2). In these years, 101 kg N ha^{-1} was needed with NT to match yields with CT and MT treatments. In 1995, in addition to the low yields with NT at the low N rates, weed competition in this year with above-average precipitation was a problem in NT (Fig. 1), compared with CT and MT plots. In the >500 mm TPAW group, seed yields with MT and NT were generally greater than with CT, except for 1986, when the low N rates with NT resulted in lower yields than those with CT and MT.

Except for 1989, 1990, and 1994, seed yields (Fig. 7)

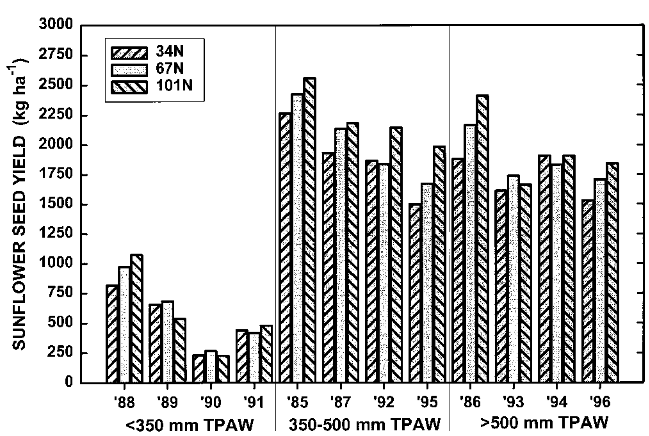

Fig. 7. Sunflower seed yield as a function of year for three N fertilizer rates grouped by level of total plant-available water (TPAW). N Rate × Year interaction LSD (0.05) = 146 kg ha^{-1}.

tended to increase with N rate above 34 kg N ha^{-1}, with the greatest responses to N fertilization occurring during the early years of the study. Lack of a larger response to N fertilization above the 34 kg N ha^{-1} rate was probably due to high spring soil NO_3–N levels, which were high throughout much of the study following the 1988 to 1990 drought (Fig. 4; Halvorson et al., 1999).

SUMMARY

Results from this study indicate that producers can include sunflower in annual dryland cropping rotations in the northern Great Plains, especially when using MT and NT systems with adequate N fertility. Sunflower seed production was greatly influenced by amount of total plant-available water. Seed production was limited by severe water stress during the 2nd and 3rd years of a 3-year drought. These results imply that sunflower will respond to available soil water located below the normal rooting depths of small grain crops such as wheat. Response to tillage system, N fertility level, and sunflower cultivar varied by year. The NT and MT systems with adequate N fertilization resulted in the highest 12-year average seed yields. Residual soil NO_3–N levels were lowest in NT and highest in CT system plots, and increased with increasing rate of N application. Sunflower produced acceptable yields in this annual cropping study, except during the 2nd and 3rd years of a continuous drought. In the 1st year of the drought, sunflower yields were probably more economical than those of spring wheat or winter wheat in the rotation. Soil water recharge at deeper soil depths was important to maintaining acceptable sunflower yields. When averaged over years, sunflower yields within the spring wheat–winter wheat–sunflower rotation were acceptable when using MT or NT systems and adequate N fertility, with profit potential equal to wheat in the rotation. Sunflower added diversity to the rotation and utilized available root-zone water supplies effectively, reducing the potential for saline-seep development. Sunflower had a positive impact on this rotation.

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